Precise and Automatic Patient Positioning in Computed Tomography: Avatar Modeling of the Patient Surface Using a 3-Dimensional Camera

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Abstract: OBJECTIVES The aim of this study was to evaluate the accuracy of a 3-dimensional (3D) camera algorithm for automatic and individualized patient positioning based on body surface detection and to compare the results of the 3D camera with manual positioning performed by technologists in routinely obtained chest and abdomen computed tomography (CT) examinations. MATERIALS AND METHODS This study included data of 120 patients undergoing clinically indicated chest (n = 68) and abdomen (n = 52) CT. Fifty-two of the patients were scanned with CT using a table height manually selected by technologists; 68 patients were automatically positioned with the 3D camera, which is based on patient-specific body surface and contour detection. The ground truth table height (TGT) was defined as the table height that aligns the axial center of the patient's body region in the CT scanner isocenter. Off-centering was defined as the difference between the ground truth table height (TGT) and the actual table position used in all CT examinations. The t test was performed to determine significant differences in the vertical offset between automatic and manual positioning. The test was used to check whether there was a relationship between patient size and the magnitude of off-centering. RESULTS We found a significant improvement in patient centering (offset 5 ± 3 mm) when using the automatic positioning algorithm with the 3D camera compared with manual positioning (offset 19 ± 10 mm) performed by technologists ($P < 0.005$). Automatic patient positioning based on the 3D camera reduced the average offset in vertical table position from 19 mm to 7 mm for chest and from 18 mm to 4 mm for abdomen CT. The absolute maximal offset was 39 mm and 43 mm for chest and abdomen CT, respectively, when patients were positioned manually, whereas with automatic positioning using the 3D camera the offset never exceeded 15 mm. In chest CT performed with manual patient positioning, we found a significant correlation between vertical offset greater than 20 mm and patient size (body mass index, >26 kg/m, $P < 0.001$). In contrast, no such relationship was found for abdomen CT ($P = 0.38$). CONCLUSIONS Automatic individualized patient positioning using a 3D camera allows for accurate patient centering as compared with manual positioning, which improves radiation dose utilization.

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Precise and Automatic Patient Positioning in Computed Tomography

Avatar Modeling of the Patient Surface Using a 3-Dimensional Camera

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Objectives: The aim of this study was to evaluate the accuracy of a 3-dimensional (3D) camera algorithm for automatic and individualized patient positioning based on body surface detection and to compare the results of the 3D camera with manual positioning performed by technologists in routinely obtained chest and abdomen computed tomography (CT) examinations.

Materials and Methods: This study included data of 120 patients undergoing clinically indicated chest (n = 68) and abdomen (n = 52) CT. Fifty-two of the patients were scanned with CT using a table height manually selected by technologists; 68 patients were automatically positioned with the 3D camera, which is based on patient-specific body surface and contour detection. The ground truth table height (T_{GT}) was defined as the table height that aligns the axial center of the patient's body region in the CT scanner isocenter. Off-centering was defined as the difference between the ground truth table height (T_{GT}) and the actual table position used in all CT examinations. The *t* test was performed to determine significant differences in the vertical offset between automatic and manual positioning. The χ^2 test was used to check whether there was a relationship between patient size and the magnitude of off-centering.

Results: We found a significant improvement in patient centering (offset 5 ± 3 mm) when using the automatic positioning algorithm with the 3D camera compared with manual positioning (offset 19 ± 10 mm) performed by technologists $P < 0.005$). Automatic patient positioning based on the 3D camera reduced the average offset in vertical table position from 19 mm to 7 mm for chest and from 18 mm to 4 mm for abdomen CT. The absolute maximal offset was 39 mm and 43 mm for chest and abdomen CT, respectively, when patients were positioned manually, whereas with automatic positioning using the 3D camera the offset never exceeded 15 mm. In chest CT performed with manual patient positioning, we found a significant correlation between vertical offset greater than 20 mm and patient size (body mass index, >26 kg/m^2, $P < 0.001$). In contrast, no such relationship was found for abdomen CT ($P = 0.38$).

Conclusions: Automatic individualized patient positioning using a 3D camera allows for accurate patient centering as compared with manual positioning, which improves radiation dose utilization.

Key Words: CT, tube current modulation, AEC, automatic patient positioning, 3D camera

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With the introduction of faster scanning techniques and improved software and hardware technologies, the number of computed tomography (CT) examinations has been growing rapidly. As a consequence, the medical community, physicians, and manufacturers have been developing techniques for radiation dose optimization and reduction such as low tube voltage scanning, bowtie filtering, adaptive collimation, and iterative image reconstruction.[1–4] Another major technique for optimizing the radiation dose of CT examinations is tube current modulation (TCM). Several previous studies reported that TCM enables dose reduction up to 60% without compromising the image quality of the examination.[5–7]

Although the implementation of TCM varies between vendors, the applied tube current values always are based on estimates of patient size using information obtained from projection localizer radiographs (LRs).[8–10] Apparently, patient size in CT localizers varies with localizer type and patient positioning in the CT gantry,[11] resulting in variation in tube current values applied by the TCM system. This implies that inaccurate centering of patients may result in magnification of the acquired LR when the patient is positioned too close to the x-ray source, leading to overestimation of the patient size. In contrast, when patients are placed further away from the x-ray source, the LR image becomes smaller and patient size is underestimated. Thus, patient positioning is crucial for accurate evaluation of patient size and optimal dose utilization for the TCM function.[8,11]

Several recent studies have indicated that inappropriate patient centering impacts the automatic TCM system behavior, which consequently affects both image quality and patient radiation dose.[12–15] Kaasalainen et al[15] has shown that patient off-centering of approximately 6 cm toward the x-ray tube can increase the radiation dose by up to 38%. Toth et al[13] showed that off-centering below the gantry isocenter can result in a surface dose penalty of up to 140%. In contrast, patient off-centering above the isocenter and thus more far away from the x-ray tube leads to substantial increases in image noise and unreliability of the CT attenuation values.[16] Recently, Saltybaeva and Alkadhi[11] has shown that patient off-centering of only 20 mm in either direction causes significant organ dose changes in chest CT performed with TCM.

Given the relevance of patient positioning on radiation dose, it is amazing that the problem of patient malpositioning has not been solved so far. Li at al[16] found that almost 95% of patients undergoing chest CT were positioned inappropriately with a mean distance from the optimal isocenter of 33 mm. Kim et al[17] investigated 397 abdominal CT examinations and found that 81% of patients were positioned off-center leading to significant changes of CT attenuation in the abdominal wall. Thus, techniques for optimized and, ideally, automatic patient positioning appear highly desirable.

Recently, a new CT scanner (SOMATOM Edge Plus; Siemens Healthineers, Forchheim, Germany) was introduced, which enables automatic table positioning with the help of a combined color/depth camera. The 3-dimensional (3D) depth sensor of the camera employs infrared light to measure the distance of objects to the camera. A virtual patient Avatar[18] is fitted to the depth data and the geometric center of the Avatar is used to automatically set the vertical table position for the LR scan. Moreover, the workflow allows also to set the horizontal

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table position and the LR scan range based on body landmarks detected by the 3D camera image and the selected scan protocol.

The aim of this study was to evaluate the accuracy of the 3D camera algorithm for automatic and individualized patient positioning based on body surface detection and to compare the results from the 3D camera with manual positioning performed by technologists in routinely obtained chest and abdomen CT examinations.

MATERIALS AND METHODS

Patient Population

This study included the data of 120 patients undergoing consecutive CT examinations in our department between March 2017 and December 2017. The data were collected and analyzed retrospectively. The study had local institutional review board approval; written informed consent was waived.

Patient Group 1

The first group included 68 patients scanned on a third-generation 192-slice dual-source CT scanner (SOMATOM Force; Siemens Healthineers, Forchheim, Germany) operated in the single-source mode. Thirty (11 female, 19 male; mean age, 63 ± 10 years; range, 42–84 years) of these 68 patients underwent CT with our routine clinical abdomen protocol; 38 patients (21 female, 17 male; mean age, 64 ± 13 years; range, 35–86 years) underwent CT with our routine chest protocol. All patients were scanned in a supine position, and the table height was manually and individually selected by the technologist performing the respective CT examination and with the help of the CT scanners built-in lasers. Technologists were instructed to center each patient as carefully as possible based on their visual estimate of the midpoint of the patient's anterior-posterior dimension.

Patient Group 2

The second group included 52 patients scanned on a single-source 128-slice CT scanner (SOMATOM Edge Plus; Siemens Healthineers, Forchheim, Germany). This scanner is equipped with the 3D camera for automatic patient positioning. Twenty-two (9 female, 13 male; mean age, 60 ± 12 years; range, 32–85 years) of these patients underwent CT with our routine abdomen protocol; thirty (12 female, 18 male; mean age, 62 ± 13 years; range, 27–91 years) underwent CT with our routine chest protocol. In all patients from group 2, the table height was automatically and individually defined by the scanner based on a single snap shot of the 3D camera mounted above the patient table (Fig. 1A). The data collection was performed after the implementation of the new CT system in our clinical routine with no additional influence on the daily workflow, the studied cohort, and the scanning parameters.

There were no significant differences among patient groups regarding age (P = 0.23), body weight (72.7 kg [range, 50–104 kg] vs 70.9 kg [range, 41–115 kg], P = 0.62), body height (168.3 cm [range, 152–183 cm] vs 168.4 cm [range, 153–195 cm], P = 0.97), and body mass index (BMI) (24.8 ± 6.2 kg/m^2 [range, 19.4–34.9 kg/m^2] vs 25.2 ± 6.3 kg/m^2 [range, 16.4–43.8 kg/m^2], P = 0.87). There were also no significant gender differences between groups (P = 0.44).

CT Data Acquisition

3D Camera

The 3D camera obtains both a conventional 2-dimensional color image and a depth image. The depth image contains distances to object surfaces in the field of view of the camera with respect to the camera image plane. The distances are measured using infrared light and the time-of-flight principle.[19] A depth surface can be recovered from the depth image (Fig. 1B). The camera is calibrated to the coordinate system of the CT scanner. An algorithm analyzes the camera images.[18] It detects anatomical landmarks such as the head top, chin, shoulders, hip, and so on, and infers the pose of the patient (eg, feet-first supine). In addition, a virtual patient Avatar is fitted to the depth data. The Avatar is a statistical shape model. During the fitting process, it assumes the pose and body proportions according to the depth data within the variations learnt from a training population. The body landmarks are used by the system to define the horizontal table position for the LR scan and the LR range according to the selected scan protocol. To set the vertical table position, the geometric center of the Avatar hull is computed for the selected LR range. The table height at which the 3D camera planning image was taken is then adjusted such that the Avatar center and thus the patient is aligned in the isocenter of the CT scanner.

The new CT system is equipped by 2 front-side and 2 back-side touch panels, allowing for protocol selection and automatic patient centering with no time penalties compared with manual patient positioning.

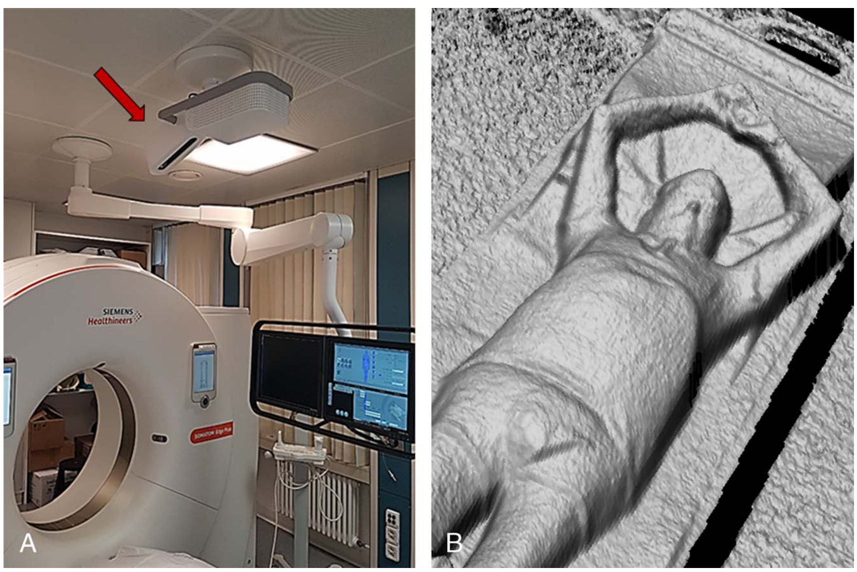

FIGURE 1. The 3D camera (arrow) is placed above the CT table (A). Three-dimensional surface image of a patient obtained with the 3D depth camera (B).

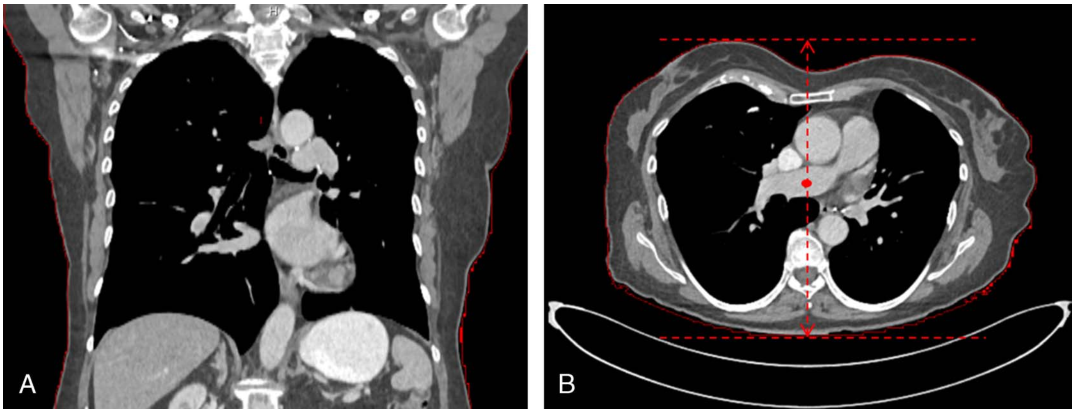

FIGURE 2. The surface of a patient (red) extracted by the software tool (A). The definition of the patient vertical center defined for each slice as the middle position between the highest and the lowest point of the extracted skin surface (B).

The system does not require any additional approval from the technologist before starting the scan; however, adjustments can be performed by the technologist manually after automatic positioning, if considered necessary.

Data Analysis

Definition of the Ground Truth

To evaluate the accuracy of automatic positioning against that performed by technologists, we compared both to the ground truth defined below. Certain components, including the bowtie filter and the TCM algorithm assume that the center of the patient's body region to be scanned is aligned in the isocenter of the scanner. Therefore, we used as the reference the ground truth table height (T_{GT}), defined as the vertical table position at which the axial center of the patient is aligned with the scanner isocenter.

The axial center of the patient was calculated retrospectively from the reconstructed slices in Digital Imaging and Communication in Medicine (DICOM) format using a software tool provided by the CT manufacturer. This tool extracts the patient surface based on attenuation thresholding (in Hounsfield Units, HU) and a region growing algorithm (Fig. 2A). The vertical center of each reconstructed slice was calculated as the middle position between the highest and lowest point of the extracted skin surface (Fig. 2B), representing the maximum antero-posterior diameter of each slice.

Finally, these diameter values were averaged along the *z*-axis of the entire scanned volume to define the ground truth axial center of each patient (Fig. 3). The axial center was mapped from patient coordinates into the coordinate system of the scanner. There, the deviation from the scanner isocenter expresses the error made by the technologist or the 3D camera algorithm when setting the manual table height T_{man} or the automatic table height T_{aut}, respectively. The ground truth table height T_{GT} was obtained as the table height that aligns the axial center of the patient's body with the scanner isocenter.

Evaluation of Vertical Off-Centering

For each patient, the table height was recorded from the DICOM header (tag: 0018, 1130). Then, the table height values for patients positioned manually (T_{man}) and those for the patients positioned automatically (T_{aut}) were compared with the ground truth table height (T_{GT}). In the end, the difference between the table positions used in the CT examination and the ground truth table height evaluated from the DICOM images was recorded for each patient in both study groups. The difference in table height corresponded to the offset of the patient from the gantry isocenter. If the table height T_{man} or T_{aut} was lower than T_{GT}, then the patient's isocenter was erroneously assumed too high and vice versa.

The average offset in chest and abdomen CT for both patient groups was calculated as the mean of the absolute offset values to avoid the influence of the offset sign on the results interpretation. This means that we evaluated only the amplitude of the offset, irrespectively of its direction. In addition, we evaluated the number of patients with an offset greater than 20 mm in each group, because such offsets are known to be associated with considerable impacts on radiation dose.[10]

Influence of the Patient Size

Previous studies reported that errors in patient vertical positioning might depend on the patient size.[13,20] To check this hypothesis, we performed correlation analysis of the vertical offset and patient size in the first study group, including manually positioned patients.

The effective diameter of the patient was used as an indicator of patient size and was calculated according to the AAPM report 204[21]:

$$D_{Eff} = \sqrt{D_{LAT} \times D_{AP}}$$

where D_{LAT} and D_{AP} corresponded to the lateral and antero-posterior diameter of the patient, respectively.

Statistical Analysis

All statistical analyses were performed using commercially available software (SPSS, release 22.0; SPSS, Chicago, IL). The Shapiro-Wilk

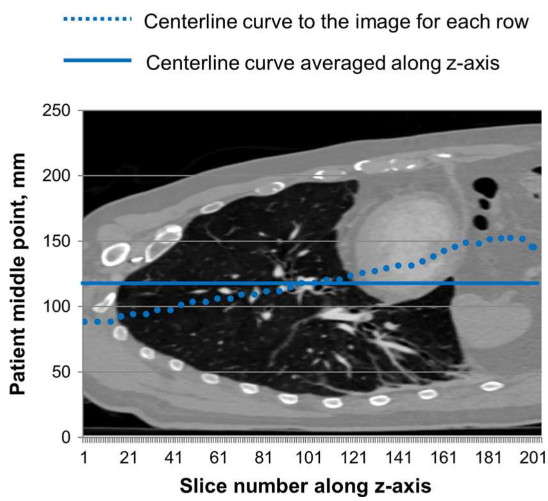

FIGURE 3. The patient vertical center, as the function of reconstructed slice number (dash line) and the average value (solid line).

TABLE 1. Average Absolute and Maximum Absolute Offset and Number of Patients With an Offset Greater Than 20 mm in Both Directions for Chest and Abdomen CT With Manual and Automatic Patient Positioning

	Average Absolute Offset, mm		Maximum Absolute Offset, mm		Patients With an Offset Above 20 mm	
Body Region of CT Examination	Automatic	Manual	Automatic	Manual	Automatic	Manual
Chest	7 ± 4	19 ± 9	15	39	0%	50% (19 of 38 cases)
Abdomen	4 ± 2	18 ± 11	9	43	0%	40% (12 of 30 cases)

test was performed to assess for normality. The Student t test for independent samples was performed to compare differences in the vertical offset between automatic and manual positioning. For the patients placed manually in both chest and abdomen CT, a χ^2 test was used to check whether there was a relationship between an offset greater than 20 mm and a patient effective diameter greater than 30 cm, which corresponded to a BMI above 26 kg/m^2 in our patient population. Spearman correlation coefficients were calculated to measure the strength of association between patient diameter and vertical offset. A 2-tailed P value below 0.05 was considered to indicate statistically significant differences.

RESULTS

Vertical Off-Centering

The main results of this study are shown in Table 1. Patient vertical off-centering was significantly reduced by using the 3D camera compared with manual positioning performed by technologists $P < 0.005$). This was observed for both chest and abdomen CT. For chest CT, the average difference in table height was 7 ± 4 mm when using automatic patients positioning with the 3D camera and 19 ± 9 mm when table height was selected manually by technologists. Representative examples of 2 patients undergoing chest and abdomen CT with manual and automatic patient centering are shown in Figure 4. The table heights are expressed as distances from the scanner isocenter down to the top of the patient table. When the diameter of the patient increases, the table needs to go further down to align that body segment with the scanner isocenter. In contrast, when the patient diameter decreases the table height curve rises.

For the abdomen, the average vertical off-centering was 4 ± 2 mm and 18 ± 11 mm for automatic and manual patient positioning, respectively. In case of manual positioning, the absolute maximal offset was 39 mm and 43 mm for chest and abdomen CT, respectively, whereas in case of automatic positioning with the 3D camera the offset never exceeded 15 mm.

The number of CT examinations with vertical off-centering greater than 20 mm in manually positioned patients was 50% (19 of 38 patients) for chest and 40% (12 of 30 patients) for abdomen CT, respectively.

Prevailing Off-Centering Direction

In chest CT, manual positioning more likely resulted in off-centering below the isocenter. In 84% of the cases (32 of 38 patients), the patient table position (T_{man}) was below the ground truth table

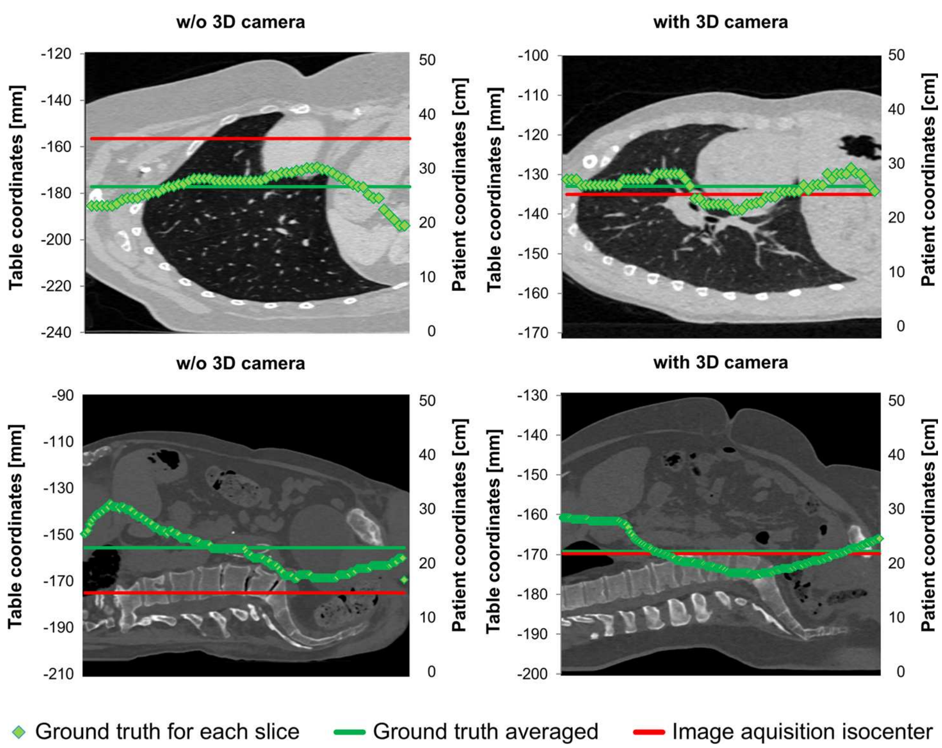

FIGURE 4. Representative examples of 2 patients who underwent chest (A and B) and abdomen (C and D) CT with manual (A and C) and automatic (B and D) patient positioning. For each patient, the ground truth table height as a function of reconstructed slice number along the z-axis (dash green), the averaged ground truth (solid green), and the actual image acquisition table height (red) are shown.

height (T_{GT}). In abdomen CT, there was no prevailing direction for off-centering, with both directions occurring with a comparable frequency (63% vs 37%).

Influence of Patient Size on Off-Centering

In chest CT, we found a significant relationship between a vertical offset greater than 20 mm and larger patient size (BMI >26 kg/m^2) and large effective diameter (>30 cm) (both, $P < 0.001$). In abdomen CT no such relationships were found ($P = 0.38$). The strength of correlation between patient diameter and vertical off-centering was moderate $Rho = 0.395$) for chest CT and very weak ($Rho = -0.144$) for abdomen CT (Fig. 5).

DISCUSSION

The TCM algorithm is one of the most important features for dose reduction and optimization in CT imaging. With this technique (angular, longitudinal, or combined automatic exposure control), tube current is adapted according to the attenuation characteristics of the body region, allowing for strong radiation dose reduction while maintaining uncompromised image quality.[6,8,22,23] However, efficient usage of the TCM function requires accurate patient positioning in the gantry isocenter of the CT scanner. Multiple studies have shown that patient vertical off-centering results in undesirable effects in regard to both radiation dose and image quality.[11–13] In general, patient off-centering can be caused by lack of proper training, lack of time in a busy clinical environment, lack of defined anatomic centering landmarks, or patient-related factors. This has encouraged the development of tools for automatic patient positioning.

First attempts using as a laser-guided prototype was described by Li et al[16] in 2007. However, this tool was not commercially released. The recently introduced CT scanner used in our study is equipped with a 3D camera and allows for automatic patient positioning based on the depth image of the patient, taking individual patient landmarks and body habitus into account. Our study systematically evaluated this technique in chest and abdomen CT examinations obtained in clinical routine.

Our results demonstrated that automatic patient positioning with the 3D camera reduces the error in patient off-centering compared with manual positioning performed by technologists. On average, the offset in table height (the distance from the ideal table position to the actual one) could be reduced from 18 mm to 5 mm by implementing the 3D camera algorithm. The offset values obtained in this study for CT with manual positioning are in agreement with previous studies reporting off-centering ranging from 3 to 60 mm, with an average of 30 mm.[15,16,20]

One of the most interesting result of our study was that in CT with automatic patient positioning the offset never exceeded 15 mm, whereas in CT examinations with manual patient positioning the offset was above 20 mm in almost 50% of the patients. According to previous studies an offset above 20 mm was associated with significant changes in radiation dose and thus should be avoided. Saltybaeva and Alkadhi[11] reported in anthropomorphic phantoms that offsets greater than 20 mm increase the radiation dose absorbed by sensitive organs by up to 38%, whereas offsets within 15 mm had no significant impact on radiation dose and image quality. These results were recently confirmed by direct dose measurement performed by Ali Khawaja et al[24] in human cadavers.

Off-centering is especially important for radiation dose absorbed by surface tissue such as the breast and thyroid gland due to the cumulative effect of tube current increases and additional effects from the bowtie shape filter. For example, when the patients is positioned too low, the surface tissues are projected to the thinnest and least attenuating part of a bowtie filter during scan rotation, resulting in higher absorbed radiation dose. Automatic patient centering helps to avoid extreme off-centering and thus eliminates excessive radiation doses to radiosensitive organs and tissue in CT performed with TCM.

It is important to note that radiation dose will not necessarily be lower when using the 3D camera as compared with manual patient positioning, but radiation dose is rather optimized and the desired image quality (which is strongly related to the tube current) is maintained. In addition, the manner in which appropriate positioning affects the radiation dose and image quality may be greater or smaller depending on the patient size. Because TCM techniques tend to reduce dose in smaller patients and increase dose in larger patients, smaller patients are more likely to have an unintentional increase in image noise caused by inappropriate beam attenuation from bow-tie filters as a result of off-centering.[15,24]

Our study has shown a moderate correlation between vertical offset and patient size undergoing chest CT. We found that larger patients (BMI > 26 kg/m^2) were manually malpositioned to a greater extent than smaller patients. These observations are supported by results published by Toth et al[13]; however, in the study of Kaasalainen et al,[15] malpositioning was more pronounced for smaller patients. Certainly, this effect depends on many factors including the experience of the operating technologist.

In our study, the majority of patients undergoing chest CT with manual positioning were positioned below the isocenter. Similar findings were observed also by Li et al.[16] This can be explained by the fact that the upper chest region, which appears slightly bigger than the lower chest, especially in female patients, is more closely located to the gantry built-in lasers and might be more commonly used by technologists as a reference for table height adjustments. In manual positioning of abdomen CT, we found no prevailing direction of off-centering, most probably due to the smaller variation in anatomy in this body part.

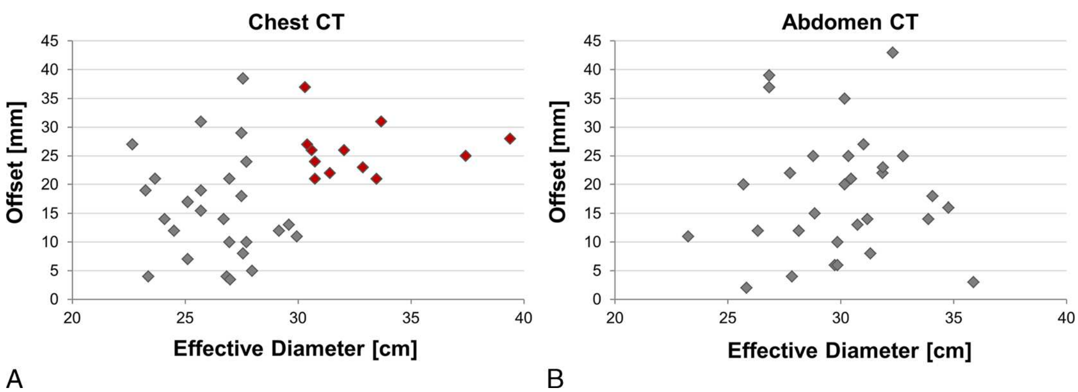

FIGURE 5. Absolute values of vertical offset for chest (A) and abdomen (B) CT with manual patient positioning as a function of patient size. The red dots correspond to patients with an effective diameter greater than30 cm and an offset greater than 20 mm.

In both chest and abdomen CT with automatic centering, there was no prevailing direction for off-centering.

Our study suffers from some limitations. First, we focused on vertical off-centering and did not investigate the effect of offset on radiation dose absorber by tissues. Nevertheless, based on the results from recent studies,[11,13] we can assume that improvement in patient centering enables a more efficient utilization of the TCM function and results in optimized radiation doses, especially regarding the dose imparted to superficial organs such as the breast and thyroid gland Saltybaeva and Alkadhi.[11] Second, the study has included only 2 body regions (ie, the chest and abdomen), and other body regions such as the head and neck were not investigated. Finally, the study was conducted in a single hospital and the attitude of our technologist team may vary from those of other departments. Finally, our study was performed on adults and did not include pediatric patients. It is important to note that radiation dose optimization is even more important in children, and smaller body size accentuates the importance of accurate patient centering.

In conclusion, our study indicates that automatic patient positioning using an algorithm based on 3D patient surface detection with a camera optimizes patient centering, which guarantees an optimized application of radiation dose to each individual patient.

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